Production of an economic high-density concrete for shielding megavoltage radiotherapy rooms and nuclear reactors

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Background: *In megavoltage radiotherapy rooms, ordinary concrete is usually used due to its low construction costs, although higher density concrete are sometimes used, as well. The use of high-density concrete decreases the required thickness of the concrete barrier; hence, its disadvantage is its high cost. In a nuclear reactor, neutron radiation is the most difficult to shield. A method for production of economic high-density concrete with appropriate engineering properties would be very useful.* ***Materials and Methods:*** Galena (PbS) mineral was used to produce of a high-density concrete. Galena can be found in many parts of Iran. Two types of concrete mixes were produced. The water-to-concrete (w/c) ratios of the reference and galena concrete mixes were 0.53 and 0.25, respectively. To measure the gamma radiation attenuation of Galena concrete samples, they were exposed to a narrow beam of gamma rays emitted from a cobalt-60 therapy unit. ***Results:*** The Galena mineral used in this study had a density of 7400 kg/m^3. The concrete samples had a density of 4800 kg/m^3. The measured half value layer thickness of the Galena concrete samples for cobalt-60 gamma rays was much less than that of ordinary concrete (2.6 cm compared to 6.0 cm). Furthermore, the galena concrete samples had significantly higher compressive strength (500 kg/cm^2 compared to 300 kg/cm^2). ***Conclusion:*** The Galena concrete samples made in our laboratories had showed good shielding/engineering properties in comparison with all samples made by using high-density materials other than depleted uranium. Based on the preliminary results, Galena concrete is maybe a suitable option where high-density concrete is required in megavoltage radiotherapy rooms as well as nuclear reactors. **Iran. J. Radiat. Res., 2007; 5 (3): 143-146**

Keywords: *High-density concrete, galena, shielding, megavoltage radiotherapy.*

INTRODUCTION

Concrete, composed of Portland cement, sand, aggregate (stones, gravel, etc.), and water [(1)], is one of the most common materials used in the construction of commercial buildings. Its properties make concrete an excellent choice for structures, cladding systems and floor slabs. On the other hand, concrete is widely used for radiation shielding in radiotherapy facilities and nuclear reactors, and for the prevention of radiation leakage from radioactive sources, as well. Although, aggregate has been basically considered as an inert, inexpensive material, it is not truly inert and influences the performance of the concrete due to its physical and sometimes chemical properties [(2)]. Concrete is a very strong material when compressed. However, it is extremely weak in tension. The strength and other properties of concrete are dependent on how the above-mentioned four ingredients are proportioned and mixed. The maximum resistance that a concrete structure will sustain, when loaded axially in compression in a testing machine at a specified rate, is measured as the compressive strength.

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Compressive strength is usually expressed as force per unit cross-sectional area, such as mega Pascals.

Currently ordinary concrete (density about 2350 kg/m^3) or lead is widely used for superficial and orthovoltage radiotherapy rooms (IAEA 2005). The photoelectric effect is the predominant interaction of X-ray photons with high atomic number matter in this energy range, making the use of lead very efficient for shielding purposes. However, in megavoltage radiotherapy treatment rooms (often referred to as bunkers or vaults because of the large barrier thickness required for shielding), ordinary concrete is usually used (due to its very low construction costs); of course higher density concrete such as barite (density up to about 3500 kg/m^3) are sometimes used, as well.

In the energy range of megavoltage therapy, the Compton effect is the predominant interaction of gamma radiation with shielding materials. When there is insufficient space for thick concrete walls, high-density concrete may be used. Therefore, the required wall thickness will be inversely proportional to the density of the shielding material. The use of high-density concrete will cut the required thickness of an ordinary concrete barrier by approximately 50%. According to the published reports, the only disadvantage of the use of high-density concrete is its high cost. As it has been estimated, the cost of construction materials will be increased by a factor of 30 [3]. It is evident that finding a method to produce of economic high-density concrete would be a very useful solution.

On the other hand, radiotherapy linear accelerators are often being housed in places used for conventional cobalt teletherapy (particularly in Iran). Since these rooms are surrounded by other departments, the space needed for the shielding will be very critical. High-density concrete, in such cases, will minimize the required space [4].

A nuclear reactor usually requires two shields: a shield to protect the walls of the reactor from radiation damage and at reflect neutrons back into the core the same time; and a biological shield used to protect people and the environment. The biological shield consists of many centimeters of very high-density concrete. In nuclear reactors, neutron radiation is the most difficult to shield. Hydrogen is the most effective element in slowing down (thermalizing) neutrons over the entire energy spectrum. Boron is effective in capturing thermal neutrons and it releases alpha particles which are easily shielded [5]. In a nuclear reactor, as with other radiation fields, the main problem in selecting the shielding materials, is to choose the most efficient and economical shield against all existing radiations in the field. Concrete is an economical and effective material for shielding stationary reactors. As high-density materials are needed to be shielded against gamma rays, a high-density concrete is often preferred to the low density type. High-density concrete has higher linear gamma and neutron attenuation characteristics in comparison with ordinary the concrete; therefore, the use of high-density concrete leads to thinner walls. Neutron radiation is the most difficult to shield.

Galena (PbS) is the main lead mineral [6]. Other common varieties include cerussite ($PbCO_3$), plattnerite (PbO_2) and angelsite ($PbSO_4$). Galena is a latin word given to lead ore or the dross from the melted lead. Galena with a density of 7400-7600 kg/m^3 material, is almost as dense as iron. Galena can be found in many parts of Iran including Angooran and Mahdiabad (Yazd) and it is exported to the other countries; so it is not costly to be used. Galena is the most important ore mineral of lead. Its structure is identical to that of halite, NaCl. The two minerals have the same crystal shapes, symmetry and cleavage. The molecular weight is 239.27 g and the ideal composition is 86.6% lead and 13.4% sulfur. Some Galena may contain up to 1% silver in place of lead. The large volume of Galena that is processed for lead produces enough silver as a by product to make Galena the leading ore of silver. The chemical composition and physical properties of Galena are summarized in table 1.

Table 1. The Chemical and Physical Properties of Galena.

Chemical Composition	Lead Sulfide (PbS)
Molecular Weight	239.26 g
Lead Content	86.59 % Pb 13.40 % S
Hardness	2.5
Specific gravity	7.6
Color	lead-gray

MATERIALS AND METHODS

In the present study, Galena mineral was used to produce of a high-density concrete. The mineral was obtained from a mine in Firouzabad (Fars). The concrete mix design was selected according to basic protocols of the study. Two types of concrete mixes were produced. Reference concrete mixes consisted of sand (945 kg/m^3), filler (214 kg/m^3), cement (920 kg/m^3), and water (180 kg/m^3). The water-to-concrete (w/c) ratio was 0.53. In the Galena sample, 1300 g of Galena mineral was used to replace sand completely in a total of 1811 g concrete mixture. In this sample the w/c ratio was 0.25. To measure the gamma radiation attenuation of Galena concrete samples, they were exposed to a narrow beam of gamma rays emitted from a Theratron cobalt-60 therapy unit (MDS Nordion, Canada) in our radiotherapy department (Namazi hospital, Shiraz).

RESULTS

The Galena mineral used in the study had a density of 7400 kg/m^3. The concrete samples made in this project had a density of 4800 kg/m^3 in comparison to that of ordinary concrete (2350 kg/m^3) or barite high-density concrete (up to 3500 kg/m^3). The measured half value layer (HVL) thickness of Galena concrete samples for cobalt-60 gamma rays (1.25 MeV) was much less than that of ordinary concrete (2.6 cm compared to 6.0 cm). Furthermore, Galena concrete samples had a significantly higher compressive strength (500 kg/cm^2 compared to 300 kg/cm^2). The comparison of engineering/shielding properties of Galena concrete samples to those of ordinary concrete are presented in table 2.

Table 2. The engineering/shielding properties of the Galena Concrete sample compared to those of ordinary concrete.

	Density (kg/m^3)	HVL for 1.25 MeV Energy Gamma Radiation (cm)	Compression Strength (kg/m^2)
Ordinary Concrete	2500	5.25-6.2	300
Barite Concrete [11]	3180-3550	3.6-4.0	140-394
Barite Concrete [12]	3490	3.8	NI
Barite Concrete [13]	NI	4.4	NI
Super Heavy Concrete [10]	3800-4200	NI	NI
Galena Concrete	4200-4600	2.56	500

NI: Not indicated by the authors

DISCUSSION

Concrete samples made of Galena showed a significantly better performance in radiation shielding, and compressive strength in comparison to ordinary concrete. Based on the preliminary results obtained, Galena concrete showed to be a highly suitable option where high-density concrete is required in megavoltage radiotherapy rooms, as well as nuclear reactors. It should be noted that the most common material for shielding the radiation from particle accelerators has been concrete. As mentioned, concrete could be made using various materials of different densities as aggregates. These different concrete mixes can have very different attenuation characteristics [7]. Kan *et al.* (2004) [8] added iron ore to concrete. They found that the compressive strength of heavy concrete increased with iron ore content, while the tensile strength declined. In their study, the concrete including 40% metallic aggregate content and the volume showed higher compressive strength and fracture toughness. It is also possible to increase efficiency, specific characteristics and safety of metal-concrete casks (shielding materials for casks used for spent nuclear fuel transportation and storage) by the use of highly dense depleted uranium dioxide (UO2) into concrete composition [9].

The Galena concrete samples made in this study showed a good shielding/engineering properties comparing to all the other samples made by high-density materials other than depleted uranium (DU). Considering the possible hazards of DU, it can be claimed that the Galena concrete can be a substitute non-radioactive shield for applications such as shielding megavoltage radiotherapy rooms. To highlight the importance of Galena concrete in shielding, its properties can be compared with to the heavy-concrete samples for which specifications have been reported in some recent publications.

In 2005, in an attempt to produce heavy concrete for protection against radiation, Proshin *et al.* produced concretes with densities of 3800-4200 kg/m^3, which the authors have called "Superheavy High-Strength concrete" [10]. They used waste products of heavy silicate-lead glasses. Bouzarjomehri *et al.* [11] produced heavy concrete samples using barite mineral. The samples they made had densities in the range 3180-3550 kg/m^3. The measured HVL for 1.25 MeV energy gamma radiation and compressive strength of their samples were 3.6-4.0 cm and 140-394 kg/m^2, respectively. Therefore, results obtained in the study indicate better physical properties of the reported high density concrete in comparison with those reported by other investigators.

ACKNOWLEGMENT

The authors wish to thank Dr. F. Faghihi and Mrs. S. Mehdizadeh at the Shiraz University for their technical advice, and Dr. F. Bouzarjomehri at Yazd University of Medical Sciences for his constructive comments. The authors also wish to thank Dr. K. Raygan Shirazi from Radiology Department of Shiraz University of Medical Sciences for his support.

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